Energy Conversion and Management 226 (2020) 113580

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Assessing the wind energy potential of China in considering its variability/intermittency

Yang Gao [a,b], Shaoxiu Ma [a,c,*], Tao Wang [a], Tongliang Wang [a,b], Yulai Gong [a,b], Fei Peng [a,c], Atsushi Tsunekawa [d]

[a] Key Laboratory of Desert and Desertification, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] International Platform for Dryland Research and Education, Tottori University, Tottori, Japan
[d] Arid Land Research Center, Tottori University, Tottori, Japan

ARTICLE INFO

Keywords:
Wind energy
Energy storage system
Technical and economic potential
Dryland

ABSTRACT

While wind energy experienced massive deployment in the last decades, the intermittency of wind energy hindered its usage and hence leads to curtailment. It is imperative to quantify and mitigate the intermittency/variability of wind energy for research community as well as industry, but there are no consensus methods yet. The present study took the first attempt to quantify the cost of the variability/intermittency of wind energy with battery energy storage system, aiming at comprehensively assessing the spatial distribution of the exploitability of wind energy in China. The research found that the most abundant wind resources are located in Tibet Plateau, Hexi Corridor, Inner Mongolia in considering the abundance of wind resources, land use type, and landforms, as well as the variability of wind energy. In the near future, wind farms with the advanced energy storage technology in 2030 or 2050 could provide stable wind energy with marketing comparable prices, which is lower than the price of current coal-fired electricity (about 0.5 CNY/kWh). It is worth to note that the variability of wind energy in Qinghai Tibet Plateau could lead to high demanding of storage capacity and therefore unaffordable cost. The proposed methodology can be applied in different regions worldwide. The results of this study could also be a scientific foundation for policy makers for wind power development in China mainland.

1. Introduction

Wind power, one of the most promising renewable energies, experienced large deployment in the last decades. It is estimated that wind power reserves above 400 million MW, which greatly exceeds the present total primary energy supply of 18 million MW [1] but generate only 5% of the greenhouse gas emissions of coal-fired power generation [2]. The cumulative installed capacity of wind power increased from 23,900 MW in 2001 to 651,000 MW in 2019 [3]. Global new wind power installations in 2019 surpassed 60,000 MW. Out of these 60,000 MW, China accounts for 43.3%, followed by the USA (15.1%), and United Kingdom (4%).

The wind power industry has grown rapidly since 2006 in China. In 2019, the installed wind power capacity is about 26,000 MW, and the accumulated installed capacity reaches 236,000 MW up to 2019, ranking first in the world [4]. However, the basic scientific research lags behind that of industrial development in China's onshore wind energy development [5]. The lack of early evaluation of wind energy resources leads to low availability and a high rate of power curtailment, which hindered the further expansion of wind energy [6]. The curtailment rates in Gansu and Xinjiang province were as high as 47% and 45% in 2016 [7], and the national curtailment power reached 27.7 million MWh in 2018.

The comprehensive assessment of the feasibility of wind energy deployment is essential for wind energy deployment as it provides scientific support for policymakers in the wind farm site selection. A number of studies were carried out to assess global onshore [8] or offshore wind energy potential [9]. And several studies revealed the technical and economic potential for wind power development on a national scale such as USA [10], Germany [11], Portland [12], Turkey [13], Sweden [14] or Nigeria [15].

Recently, the abundance and variability of wind energy in China

* Corresponding author at: Key Laboratory of Desert and Desertification, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China.
E-mail address: shaoxiuma586@163.com (S. Ma).

https://doi.org/10.1016/j.enconman.2020.113580
Received 29 July 2020; Received in revised form 13 October 2020; Accepted 19 October 2020
Available online 2 November 2020

Table 1
Overview of the data source.

Data	Spatial resolution	Time	Data Source
Wind speed	0.625° × 0.5°	1980 – 2009 (1 h)	MERRA-2
Slope	90 m × 90 m	2000	GS Cloud
Land use	1 km × 1 km	2015	REDCP

MERRA-2: Second Modern-Era Retrospective analysis for Research and Applications
GS Cloud: Geospatial Data Cloud
REDCP: Resource and Environment Data Cloud Platform.

were assessed. The spatial distribution of onshore wind energy in China was assessed by using historical data from meteorological stations [16]. The spatial and temporal distribution of wind abundance and variability in China mainland was also assessed based on the reanalysis data such as Second Modern-Era Retrospective analysis for Research and Applications (MERRA-2). Technical and economic potential in different areas were estimated and compared based on the power output data of the existing wind farms [17]. The countrywide wind power potential in China was assessed based on model output data [18]. All the above researches indicated that wind energy is abundant in the Qinghai-Tibet Plateau and Northern China.

While previous studies contributed to comprehensively assess the exploitability of wind power, none of them taken the variability of wind power into account even through the variability of wind power is a significant factor in regulating the integration of wind power into the electricity network. It is imperative to consider the variability of wind power to quantitively assess the spatial and temporal distribution of exploitable wind power.

Researchers found that the energy storage systems (ESS), especially battery energy storage systems (BESS), can mitigate the intermittency and fluctuations of wind energy [19]. In Japan and the United Kingdom, BESS has been installed for wind farms to balance wind power intermittency [20]. However, the effectiveness of BESS in mitigating the intermittency and variability of wind power is not clear in the wind energy resources assessment [21].

The aim of this study is therefore a comprehensive assessment of the onshore wind energy potential of China mainland, taking into account its variability/intermittency by applying a novel method. The specific objectives are: 1)assessing the onshore wind energy potential comprehensively including the wind resources abundance as well as land use and terrain, 2) proposing a novel approach to price the variability/intermittence of wind power, 3) re-evaluating the technical and economic potential for China's onshore wind development in considering the variability of wind power.

2. Material and methods

Three types of wind power potential were used to assess the wind power by including factors from nature resources only, to technical as well as economic factors etc. Theoretical potential only takes nature sources (wind speed) into account and the wind power density (WPD) is used to quantify its quantity as previous studies [22]. Technical potential is defined by not only including wind speed, but also technical factors such as the type of wind turbine, the transmission of network, the distance to transport network, land use type, and land forms. [23]. The economic potential is defined by including the economic factors such as operation, maintenance cost and other related cost in addition nature resources and technical factors which used to estimate technical potential [24]. The widely used Levelized cost of generating electricity

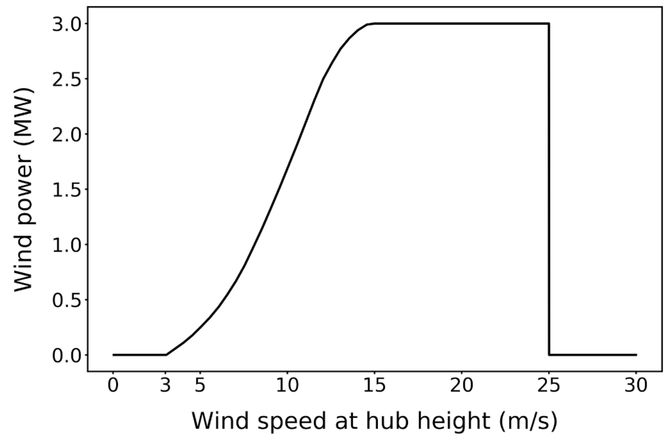

Fig. 1. Power curve of the hypothetical wind turbine model. Cut in speed = 3.5 m/s, rated speed = 15 m/s, cut out speed = 25 m/s.

(LCOE) was applied to measure the economic potential.

In this study, the wind speed data was derived from MERRA-2 reanalysis data (1980–2009), this data was validated and adopted to assess the wind resources in China [25]. The slope dataset is processed from the digital elevation data (DEM) with a spatial resolution of 90 m in China and processed by the Slope function of the "Spatial Analyst" module of ArcGIS 9.2. The slope dataset was provided by the Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn). The land use dataset was generated through manual visual interpretation based on Landsat TM/ETM remote sensing images in 2015. The land use data were provided by the Resource and Environment Data Cloud Platform (http://www.resdc.cn/Default.aspx). The sources of the dataset and their temporal-spatial resolution were shown in Table 1.

2.1. Theoretical potential of wind energy calculation

Wind speed at the wind turbine hub height is the most initial index to describe the intensity of wind as well as wind power density. Most meteorological station and model output datasets only provide the surface wind speed at 10 m height [26]. This study assumed that wind turbines with 80 m hub height will be used to exploit onshore wind power in the near future. Different extrapolation methods such as power law [27] and log law [28] method are available to extrapolate the wind speed to hub height. As more site-specific information (friction velocity, zero plane displacement and roughness length) was taken into consideration, the log law (Eq. (1)) of wind profile was considered to be more appropriate for application purpose in the industry. And this approach has been widely used in previous assessments of the wind resource in USA [29], Australia [30], Arabian Peninsula [31], and China mainland [32,33]. The log law was applied in this study to extrapolate wind speed to 80 m.

$$V(h) = \left(\frac{u_*}{k}\right) log\left[\frac{(h-d)}{z_0}\right] \tag{1}$$

where $V(h)$ is wind speed at height h, u_* is the friction velocity, k is the Von Karman constant, d is the displacement length and z_0 is the roughness length. In Eq. (1), the atmosphere is assumed to be neutrally stratified and the mentioned variables are available in the MERRA-2 dataset.

Wind power density (WPD, W/m^2) is extensively used to quantify the

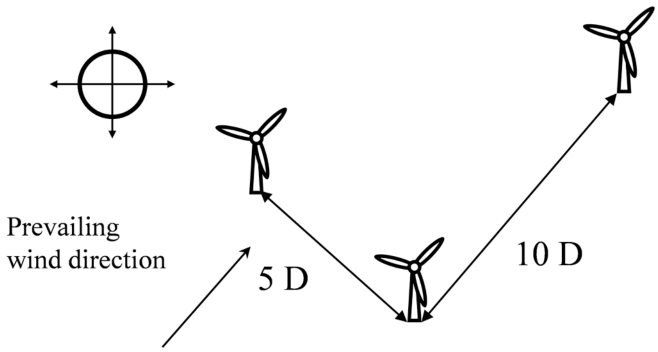

Fig. 2. Schematic diagram of turbine spacing rules.

Table 2
Land use types and its suitability factors.

Land class label	Description	Suitability Hoogwijk et al. [22]	Bosch et al. [38]	This study
11	Paddy field		0	0
12	Rainfed croplands	0.7	0.7	0.7
21	Forest land	0.1	0.2	0.1
22	Shrubland	0.5	0.5	0.5
23	Open forest land		0.65	0.65
24	Other woodland		0.8	0.7
31	High coverage grassland (greater than50%)	0.8	0.8	0.8
32	Moderate coverage grasslands (20–50%)			0.8
33	Low coverage grassland (5–20%)	0.9		0.8
41	River and canals		0	0
42	Lakes		0	0
43	Reservoirs and pits		0	0
44	Permanent snow and ice		0	0
45	Tidal flat		0	0
46	Beach land		0	0
51	Urban and town land		0	0
52	Rural residential area		0	0
53	Other construction land		0	0
61	Hot desert	1		1
62	Gobi			1
63	Saline and alkaline land			1
64	Wetland		0	0
65	Bare land		0.9	1
66	Bare rock			0.6
67	Other (Alpine desert and tundra)		0	0
99	Ocean		0	0

abundance of wind resource and is known to measure the theoretical potential of wind energy [23] as shown by Eq. (2).

$$WPD = \frac{1}{2}\rho V^3 \tag{2}$$

where V is wind speed at 80 m height and ρ is the air density, taken equal to 1.225 kg/m^3 [34].

Table 3
Values of economic input parameters used in this study.

Economical parameter	Notation	Unit	Quantity	Reference
Initial investment cost	I_C	CNY/kW	5500	[44]
Operation and maintenance cost	$O\&M$	CNY/kWh	0.1	[45]
Interest rate	i	%	5	[17]
Life time of wind turbine	t	year	20	[14]

Table 4
wind power curtailment rate in China (%).

Reference	[7]	[45]	[5]	[32]	[50]	This study
Curtailment rate (%)	10–17.1	20	15–20	17.09	8–17	15

2.2. Modelling the technical potential of wind energy

The dominant factors of technical potential of wind energy include the wind speed at turbine hub height, the technology of wind turbine and its layout, the availability of the land, and the slope of the landform [12]. Hence, these factors were taken into account to model the technical potential of wind energy in this study as it was commonly done in previous studies [14].

Based on the value ranges of key parameters of the commonly used onshore wind turbines produced by several major wind turbine manufactures (Siemens, Vestas, GE Renewable Energy, and Enercon). A hypothetical wind turbine model was assumed to be used for wind power generation. The key parameters setting of the wind turbine model was shown in Table A1, and the power curve (Fig. 1) was derived from manufacturer data [35].

The layout of the wind turbine is an important factor in maximizing the wind turbine capacity as the condensed arrangement of wind turbines would cause wake effect losses, which could lead significant loss of wind energy [36]. The wind loss could be limited within 10% if wind turbines rows are 10 D spaced out in the down-wind direction and 5 D in the cross-wind direction (D is rotor diameter of wind turbine, 100 m) [37]. The spacing rules illustrated in Fig. 2 was applied in this study, so the wind turbine density (δ) is 2/km^2 if the land area were completely used.

Land availability also plays an essential role for wind power exploitation as cities, forests, water reserves and slope hilly areas are not suitable for wind farms [22]. In this study, land use type and slope were taken into account to exclude the unavailable land for wind farms. The suitability for wind power development varies greatly among different land use types [38]. This study is following the widely used weight for the suitability of different land use type (details shown in Table 2). The original land use data in 1 km resolution was integrated into 50 km with Eq. (3). For the convenience of calculation, the land use data was then re-grided to the spatial resolution of wind speed data.

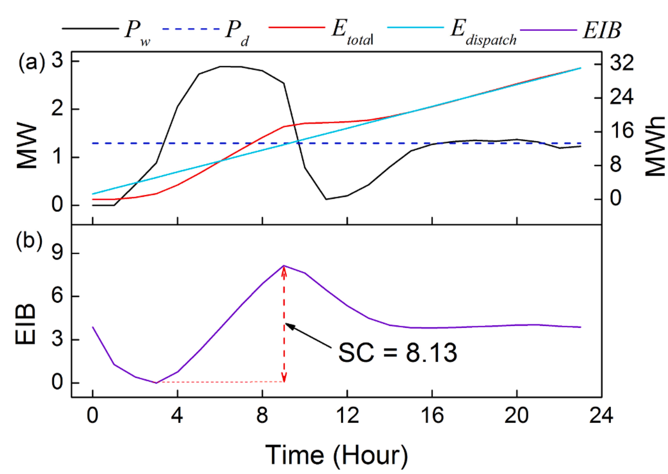

Fig. 3. An example of proposed method of determining $\boldsymbol{P_d}$ and $\boldsymbol{SC}$ at a sample point (35°N, 90°E) on 2000.1.1. a). $\boldsymbol{P_w}$ is the power generated by a turbine, $\boldsymbol{P_d}$ is the dispatched stable power. $\boldsymbol{E_{total}}$ is the total amount of power generated by a turbine, and $\boldsymbol{E_{dispatch}}$ is the stable dispatched output power b) The curve of storage energy in BESS (***EIB***), and the minimum storage capacity (***SC***) required by BESS. The 90th quantile of the 30-year daily ***SC*** was taken as the ***SC*** to be installed for wind turbine in every cell in China onshore mainland to exclude the influence of extreme value.

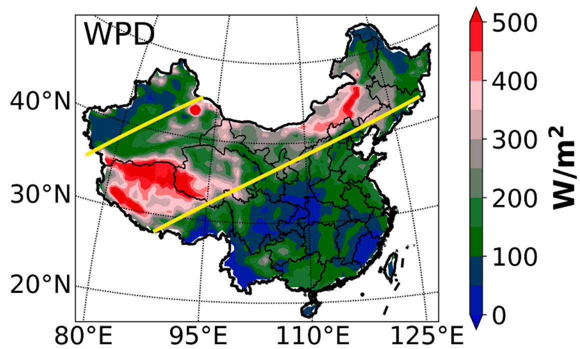

Fig. 4. Theoretical potential of wind power (WPD: wind power density) in China.

$$\eta_{lf} = \frac{\sum_1^n Suitability \times cellarea}{Totalarea} \tag{3}$$

where η_{lf} is land use suitability factor, n is the cell number in a 50 km resolution cell, which is 2500, *cellarea* is 1 km^2 and *Totalarea* for integrated cell is 2500 km^2.

Slope is another limiting factor for wind turbine installation. It was recommended that wind turbines should not install on the land with a slope gradient higher than 20° in 200 m spatial resolution [39]. Hence, the slope data (90 m resolution) were interpolated to 200 m by bilinear interpolation method at first, and Eq. (4) was used to integrate to 50 km and then re-grided to the same spatial resolution with wind speed data.

$$\eta_{sf} = \frac{Numberofcellwithslope < 20^{\circ}}{Totalnumberofcell} \tag{4}$$

The technical potential (TP, kWh/km^2) were estimated as Eq. (5) [40]:

$$TP = T \times EWP \times \eta_{av} \times \eta_{lf} \times \eta_{sf} \times (1 - L) \times \delta \tag{5}$$

where$T$ is the number of hours in a year of MERRA-2 data, EWP is the extractable wind power for a turbine obtained from the wind profile and selected turbine's power curve, η_{av} is the utilization efficiency of the wind turbine (97%) [14], η_{lf} and η_{sf} is land use suitability and slope suitability respectively obtained from Eq. (3) and Eq. (4) , L is the the overall loss rate of wind farms due to the wake effect, transmission, internal and other inevitable loss, equal to 15% according to [39], δ is wind turbine density, 2/km^2 according to the space rule illustrated in Fig. 2.

2.3. Modelling the economic potential of wind energy

Wind power developers and policymakers aim to a maximize economic return of the wind farm. LCOE regarded as an indicator that can be easily communicated and understood by policy makers and energy planners [41]. The interest rate was used to convert the future cost as well as benefits into present value during the lifetime of the project [42]. LCOE represents the present value, the total discounted costs divided by total production to present value [43], which reflects the investors return on capital.

The costs of wind energy production includes initial construction cost (I_C) and operation and maintenance cost ($O\&M$) during the life time (20 years) of wind turbine [42]. I_C includes turbine cost, grid connection, foundations, installation, and construction related expenses. $O\&M$ includes material costs, repair costs, maintenance costs, accidental maintenance and other costs [17]. It varies throughout the project life depending on the amount of the generated electricity [10]. The economic parameters used in this paper were shown in Table 3. LCOE was calculated with the following equation:

$$LCOE = \frac{I_C + \sum_{t=1}^{n} \frac{O\&M_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{6}$$

Where I_C is initial investment, $O\&M_t$ is operation and maintenance cost in t-th year, i is interest rate and t is life time of wind turbine.

2.4. The wind energy curtailment and mitigation strategies

The intermittency of wind posed a huge challenge for integration of wind energy into the electricity transmission networks and leaded to the significant curtailment of wind energy [46]. Studies reported that wind power curtailment is strongly related to its variability [47]. Several studies define the variability coefficient (VC) of wind power to quantify wind power variability [48], but the quantity of wind power curtailment is ambiguous and generally based on measured data in wind farms or national reports. Recently, a number of researchers studied the wind power curtailment in China (Table 4). In 2015, the National Energy Administration introduced a policy that the new installation of wind power would be limited where the curtailment rate beyond 20% [49]. In this study, the wind power curtailment rate was set as 15% (an average of previous studies) to estimate TP after subtracting wind power curtailment (Eq. (7)).

$$TP = T \times EWP \times \eta_{av} \times \eta_{lf} \times \eta_{sf} \times (1 - L) \times \delta - CurtailmentPower \tag{7}$$

Lithium-ion battery energy storage system (BESS), the best frontier

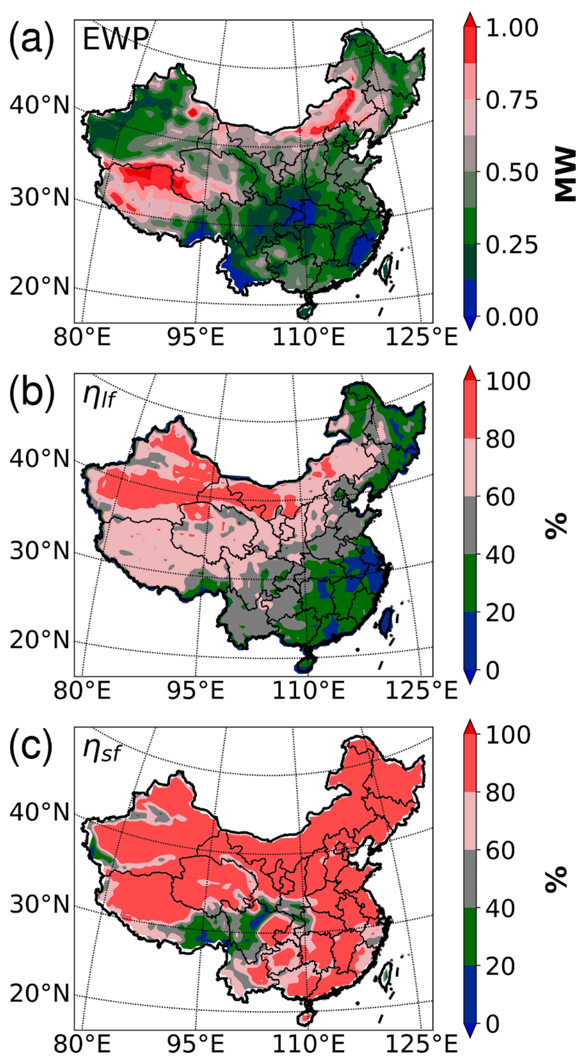

Fig. 5. The dominant factors for the wind energy technical potential in China. (a) extractable wind power (EWP), (b) land use suitability (η_{lf}), (c) slope suitability (η_{sf}).

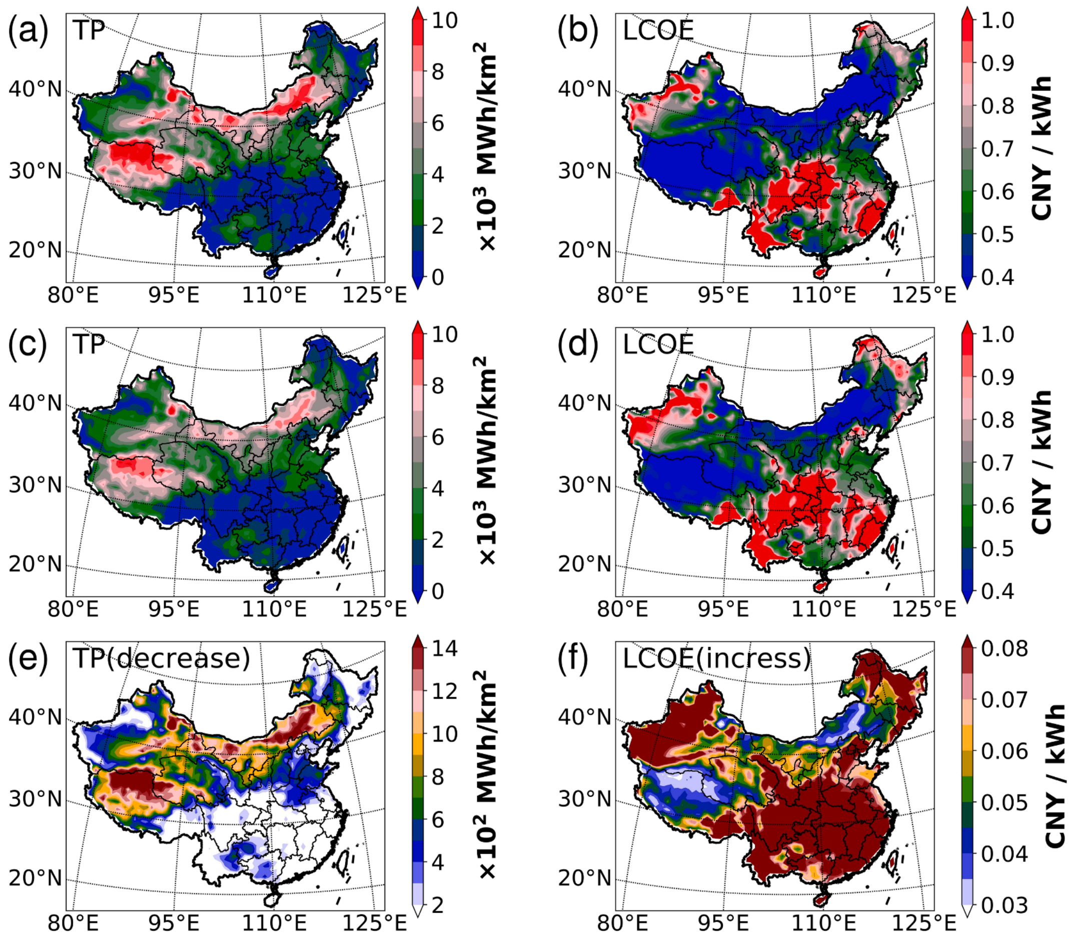

Fig. 6. (a, b) is the Technical Potential (TP) and economic potential (LCOE) for wind power development in China, (c, d) is same to (a, b) but considering wind curtailment and (e, f) is the absolute change of the TP and LCOE after considering wind curtailment.

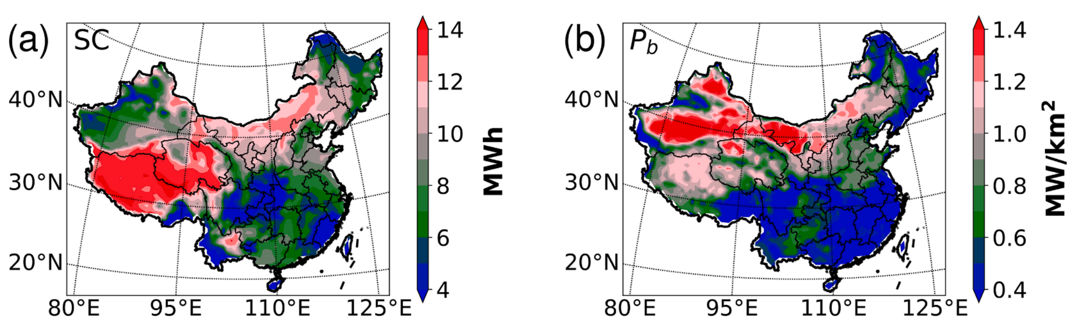

Fig. 7. The spatial distribution of the storage capacity (SC) for each turbine (a) and charge/discharge power capacity (P_b) for each square kilometer (b).

of energy storage, was adopted to mitigate and quantify the cost of the variability/intermittence of wind power thanks its advantages in fast response, good applicability as well as high efficiency (charge/discharge loss rate less than 3%, ignored) [51]. It is worthwhile to note that it will increase the running cost of wind farms to equip with BESS, but BESS can reduce the curtailment of wind energy, which could potentially offset the cost of BESS.

The cost of BESS is determined by its storage capacity (*SC*) and charge/discharge power capacity (P_b) [52]. In this study, *SC* for a single turbine in a pixel was estimated in accordance with the following methods:

The proposed method assumed that BESS balances the daily generation volatility every day as BESS can act in an hourly to daily time scale [53]. Taking wind profile of sample point in Tibet Plateau on 2000.1.1 as an example to demonstrate the wind power generation and smoothed dispatchable electricity (Fig. A1), the sample point located at 35°N, 90°E, indicated by yellow triangle in Tibet Plateau in Fig. A2. As shown in Fig. 3a, the highly variable power generated by a turbine is P_w. The wind power can be delivered to the grid with a dispatched stable power (P_d) without curtailment after passing BESS in a day. The dispatched

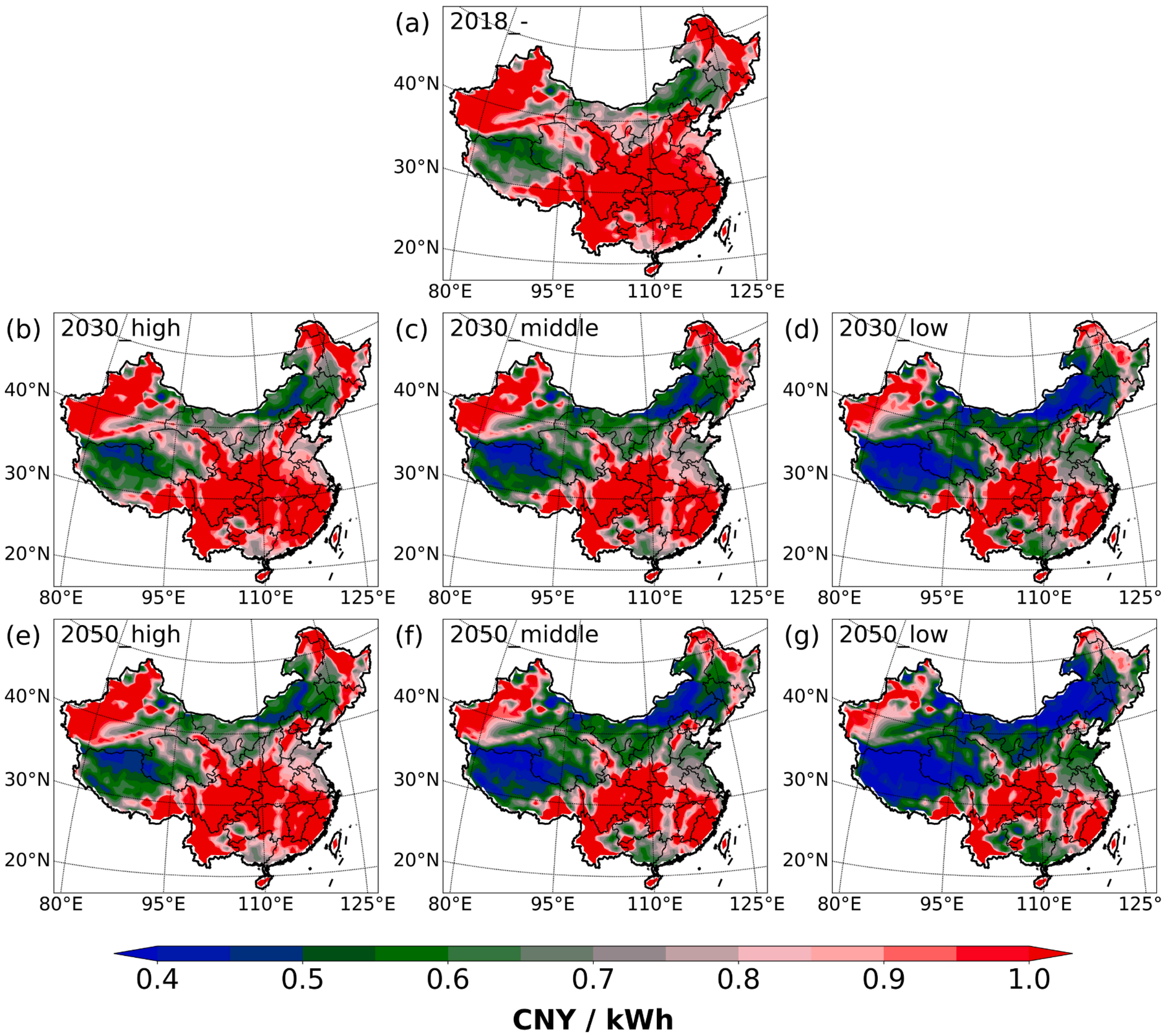

Fig. 8. Economic potential of wind energy in China with battery energy storage system (BESS) installed in 2018, 2030, 2050 (in rows) and high, middle, low price projections (in columns).

stable power is calculated as Eq. (8):

$$P_d = \frac{\int_0^{24} P_w(t)dt}{24} \tag{8}$$

As shown in Fig. 3b, the energy in BESS (*EIB*) at initial time is EIB_i, when P_w(t) >P_d, BESS is charging, otherwise, it is discharging, then*EIB* at time *t* is:

$$EIB = EIB_i + \sum_0^t [P_w(t) - P_d] \tag{9}$$

And *SC* required by BESS for a turbine is estimated as Eq. (10):

$$SC = EIB_{max} - EIB_{min} \tag{10}$$

P_b is 25% of installed capacity according to [54].

The power price of BESS ($Price_{Pb}$) is about 2000 CNY/kW (300 $/kW), and the storage price ($Price_{sc}$) is about 4200 CNY/kWh (620 $/kWh) in 2018 [55], which is expensive for the wind developer to equip it for the wind farms [56]. However, it is projected that the BESS costs will decrease rapidly with the development of technology in the near future [57]. The detailed projection of the price of *BESS* proposed three scenarios of high, medium, and low prices in 2030 and 2050 (Fig. A3, Table A3) [58]. Based on this study, the cost of the BESS ($I_{C_{BESS}}$) in 2018, 2030, 2050 were priced as:

$$I_{C_{BESS}} = I_{C_{BESS\_P}} + I_{C_{BESS\_S}} = 0.25 \times P_r \times Price_{Pb} + SC \times Price_{sc} \tag{11}$$

where $I_{C_{BESS\_P}}$ is the power cost of *SC*, $I_{C_{BESS\_S}}$ is the storage cost of *SC*, P_r is the rated power of installed capacity,$Price_{Pb}$ is the price of the charge/discharge power capacity and the $Price_{sc}$ is the price of the storage capacity.

And LCOE with BESS is estimated as:

$$LCOE = \frac{I_C + I_{C_{BESS}} + \sum_{t=1}^{n} \frac{O\&M_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{12}$$

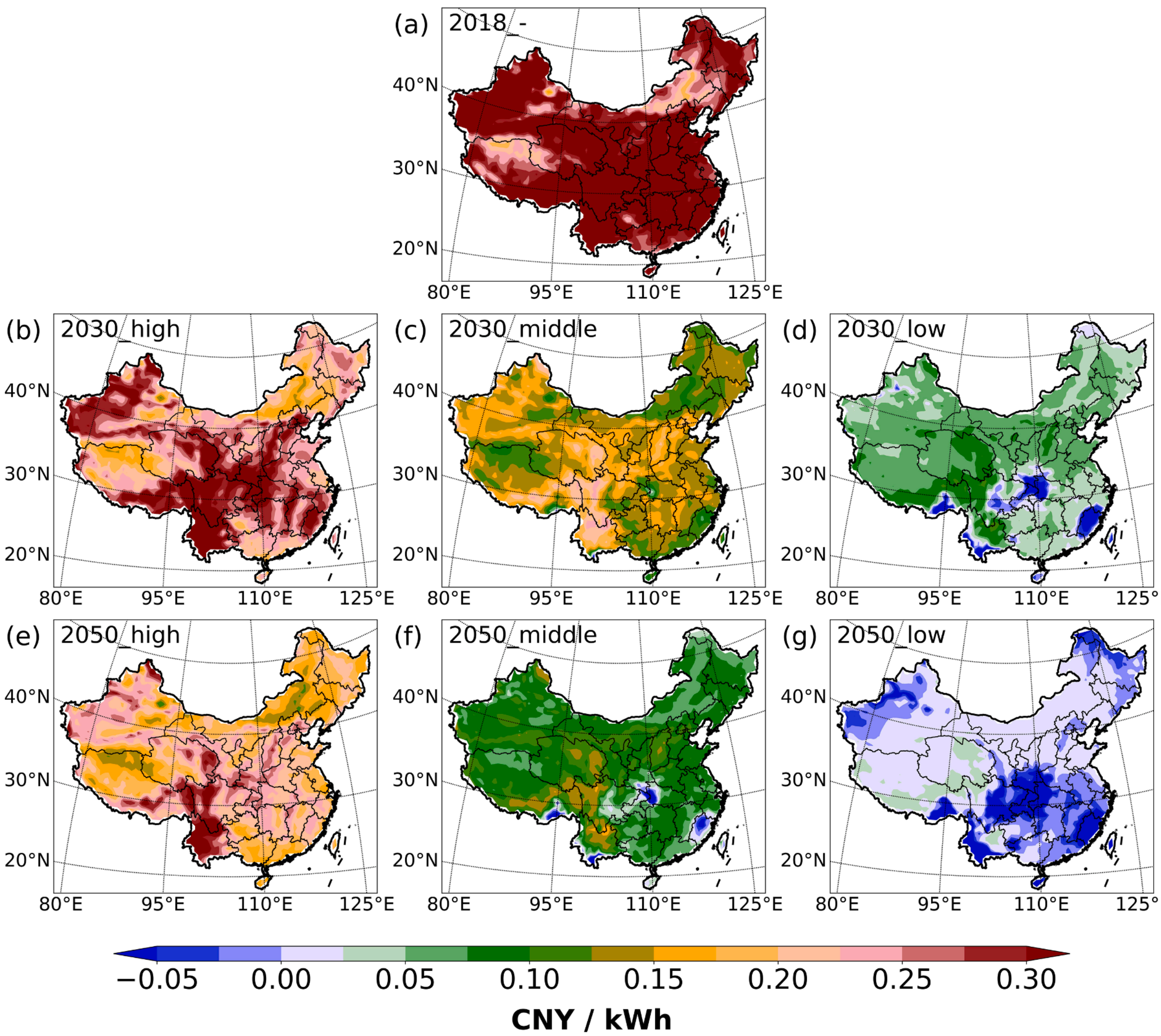

Fig. 9. The difference between the economic potential with BESS and the economic potential with wind power curtailment scenario in 2018, 2030, 2050 (in rows) and high, middle, low price projections (in columns). The change of the LCOE is the net value of BESS system after offsetting the cost of BESS with the reduce of curtailment.

3. Results

This study aimed to quantify the cost of the variability of the wind energy for the wind power potential assessment, which was ignored in the previous assessment studies. Hence, the results were grouped into two parts by ignoring the variability of wind power (Section 3.1) and by adopting the novel method to quantify the cost of variability of wind power (Section 3.2).

3.1. The wind energy potential and the wind curtailment

The abundant onshore wind energy of China distributed from the North-west to North-east, indicated as the yellow line in Fig. 4. It includes Tibet Plateau, Eastern Xinjiang, Hexi Corridor, and Eastern Inner Mongolia. Location as well as their climatic and geography character of these regions were indicated in Fig. A2 and Table A1. The annual WPD in these regions exceeds 200 W/m^2. The richest wind resources are located in the Tibet Plateau and a part of Inner Mongolia and Hexi Corridor where the WPD is beyond 350 W/m^2. In contrast, WPD is under 200 W/m^2 in the South-east (under the yellow line) and North-west (above the yellow line).

The exploitable wind energy is highly dependent on wind resources abundance [59], wind turbine type [60], the land use type, as well as the slope of landforms, etc [61]. In this study, a hypothetical wind turbine model was used to estimate EWP. The most abundant wind energy located from North-east to North-west, which is similar to the distribution of WDP (Fig. 5 a). The availability of land is another major limiting factor of wind energy exploitation. As the desert, gobi, as well as sparse grassland is widely distributed in North-western China, more than 80% of the area is suitable for the construction of wind farms (Fig. 5 b). In Eastern Inner Mongolia and Qinghai Tibet Plateau, over 60% of the land is available for wind power generation as grasslands and meadow are the main land use due to the shortage of water resources and cold climate and its low productivity. The central and south-eastern regions are farmland and densely populated, which are not suitable for installing wind turbines. The most unsuitable lands for wind farm due to the steep slope of the landform are located in the southwest and the edge of the Qinghai Tibet Plateau (Fig. 5 c).

In the absence of power curtailment, the technical and economic potential obtained from Eq. (5) and Eq. (6) is shown in Fig. 6 (a, b). The regions with the greatest technical and economic potential in China are the Qinghai Tibet Plateau, Hexi Corridor, and the Eastern Inner Mongolia, where TP reached 8000 MWh/km^2, and the LCOE is less than 0.4 CNY/kWh (the current price of electricity is about 0.5 CNY/kWh). The TP of South-eastern China is below 2000 MWh/km^2, and the LCOE is beyond 0.8 CNY/kWh. The LCOE is more than 1 CNY/kWh in the Sichuan Basin and Western Hubei Province of small wind speed, slope terrain.

The most abundant wind energy is located in Eastern Inner Mongolia, Hexi Corridor, and Qinghai Tibet Plateau after subtracting the curtailment of the wind energy, which is 15% of wind energy as reported in previous studies. TP and LCOE are about 6000 MWh/km^2 and 0.4 CNY/kWh respectively in these regions (Fig. 6 c, d). The curtailment of the wind power ranges from 800 to 1500 MWh/km^2 in Qinghai Tibet Plateau, Inner Mongolia, Eastern Xinjiang, and Hexi Corridor region (Fig. 6 e). The LCOE in these regions increases by 0.04–0.06CNY/kWh (Fig. 6 f) compared with the “no curtailment” scenario.

3.2. Mitigation of the variability/intermittency of wind energy and its cost

In order to smooth the intermittent wind energy and generate stable and usable energy, the SC and P_b of optimum BESS were calculated and presented in Fig. 7. The Qinghai Tibet Plateau is the highest demanding for SC of BESS (Fig. 7 a) to smooth the variability and intermittency of wind energy. The BESS storage capacity exceeds 14 MWh for each wind turbine. It should be highlight that the SC of BESS ranges from 10 to 12 MWh in Inner Mongolia, Hexi Corridor, and other wind resource rich regions, which is lower than that of the Qinghai Tibet Plateau. The P_b of the BESS in Xinjiang, Inner Mongolia, and Western Gansu province beyond 1 MW/km^2 (Fig. 7 b), higher than other regions since these areas are rich in wind and suitable for wind farms due to bare and flatten ground (hot desert and gobi), where the turbine can be densely distributed.

BESS cost was calculated based on the price of SC and P_b in 2018, 2030, and 2050 under different scenarios according to Eq. (11) (Fig. A4). BESS overcomes the weakness of wind energy in terms of intermittency and resolves the problem of power curtailment, but BESS increases the cost of the wind power exploitation, and lead to the decrease of economic potential for wind power development. Based on the price of BESS in 2018 or the high-price development in 2030 and 2050, the LCOE of Qinghai Tibet Plateau, Eastern Inner Mongolia, and Hexi Corridor is lower than other regions, but LCOE are still higher than 0.5 CNY/kWh in most of the areas (Fig. 8 a, b, e). However, LCOE decreases significantly within the middle and especially low-price development scenarios. The LCOE in wind rich areas are lower than 0.5 CNY/kWh in the middle price scenario (Fig. 8 c, f). The LCOE is less than 0.45 CNY/kWh in the low-price scenario in 2050 (Fig. 8 f, g).

The LCOE with BESS (Fig. 8) and the LCOE with wind curtailment (Fig. 6 d) is compared to identify how much the BESS could offset the wind power curtailment and the difference was shown in Fig. 9. LCOE with BESS with the price in 2018 (Fig. 9 a) is 0.15–0.4 CNY/kWh higher than the LCOE with curtailment over China mainland. This is too expensive and unacceptable for wind power developers. Under the middle-price scenario in 2050 (Fig. 9 f) and low-price scenario in 2030 (Fig. 9 d), the LCOE with BESS is slightly higher (0.05–0.1 CNY/kWh) than the current LCOE with curtailment. It should be highlighted that the LCOE with BESS within the low-price scenario in 2050 is equal or even lower than the LCOE with power curtailment (Fig. 9 g). Besides, although the LCOE with BESS is higher than the LCOE with power curtailment (Fig. 9 a-f), the BESS overcomes the problem of power abandoned, TP of wind resource rich areas could increase by more than 1000 MWh/km^2 (Fig. 6 e).

4. Discussion

The theoretical, technical, and economic potential of wind energy presented in this study is comparable with the results of previous studies. The most abundant of wind energy is located in Qinghai Tibet Plateau, Eastern Xinjiang, Hexi Corridor, and Eastern Inner Mongolia indicated in Fig. A2 and Table A2. In Eastern Xinjiang and Hexi Corridor, *WPD*and *TP* is about 300 W/m^2 and 8000 MWh/km^2 respectively, which is consistent with the research results of [17]. The concentrated zones for current wind farm construction in China are Hami, Jiuquan, Xilingol, and the LCOE in this study (less than0.5 CNY/kWh) agree with the price of local wind power reported in relative reports [62].

WPD in Qinghai Tibet Plateau is more than 500 W/m^2 thanks to the geographical winds and air flow acceleration caused by atmosphere uplifted (average altitude greater than 4500 m). The theoretical potential for wind power development is significantly better than Eastern Xinjiang and Hexi Corridor if focus mainly on the wind energy abundance (Fig. 4) [63]. However, *SC* of BESS in Tibet Plateau (≈14 MWh) is higher than other regions due to its high variable wind speed. *TP* in Qinghai Tibet Plateau is similar to Eastern Xinjiang and Hexi Corridor after considering land use and terrain constraints (Fig. 6 c). This is mainly benefited from the flat landform as well as the suitable land use type for wind farms (gobi, desert, and sparse grassland) in Eastern Xinjiang and Hexi Corridor, comparing with the Qinghai Tibet mountain area.

Thanks to the abundance of wind energy and extensive spare land, most of the suitable area for wind power exploitation is located in North-western China. It should be noted that North-western China is sparsely populated, traffic and electric transmission network as well as other basic infrastructure are underdeveloped. This could hinder the development of wind power and further investment is needed for in this region. The altitude of Qinghai Tibet Plateau is higher than 4500 m, which can also influence the wind power potential. It is worthwhile to include as much as possible details of the land use, and landform data in wind energy potential assessment. Meanwhile, it does also indicate that further studies should be carried out to include the distance of wind farm to cities, transport network, and transmission lines for the wind energy assessment [39], which has a significant influence on the exploitability of wind energy [41].

It is widely acknowledged that the intermittency of wind energy hindered the exploitation of wind energy as the intermittent wind energy could not be integrated into the conventional electrical transmission network and it also cannot satisfy the electricity demand of the residences [64]. Previous studies use the variability coefficient to quantify the variability and these studies contributed to quantify with a fully potential wind energy distribution map [48]. However, these methods did not quantitively assess the cost of the wind power intermittency.

Similar to the idea of the environmental economics, travel cost method (TCM), to price value of natural resources [65], BESS was introduced in this study to quantify the cost of the variability of wind energy as BESS was commonly equipped with wind farms to smooth the intermittent wind energy in practice [66]. An ideal scenario assumption, that wind farms with BESS could output stable electricity and the curtailment is zero, is used to fully price the cost of the intermittency of wind power as well as to evaluate the value of BESS to reduce the wind power curtailment. Hence the full potential of wind energy can be estimated with this assumption in this study.

With the technology development of the BESS, the price of dispatchable stable wind is comparable with the current electricity price (around 0.5 CNY/kWh). The LCOE in wind resource rich area is approximately 0.55–0.7 CNY/kWh (Fig. 8) in 2018 with BESS, which is higher than the current average price. However, studies showed that storage technology will advance rapidly in the future, and the cost of various types of storage technology will be reduced by 50–66% or more over the next 10 years [67]. The LCOE will decrease to below 0.45 CNY/kWh (Fig. 8), which is an acceptable price for wind developers.

This study showed that the cost of BESS is basically the same as the economic loss caused by “wind abandonment”, or even lower than that with the advanced BESS technology in the near future. This shows that it is a very good choice to install BESS with an appropriate scale to overcome the intermittency/variability of wind power. However, according to the method proposed in this paper, BESS can only solve the intermittency/variability of wind power on a short time scale, the stable output of the wind power needs to be adjusted every day, which increases *O&M* cost. This problem could be resolved with a smart management system to adjust the dispatched wind power with advanced artificial intelligence. Further research is needed on this topic.

Further studies are necessary to investigate following issues. The terrain, temperature, air density, precipitation and other environmental elements varies greatly in different regions, hence high resolution of data could be a great opportunity to precisely quantify the wind power potential. The policy and other relative economic factors also vary with time. Specific information is need to model the technical and economic wind power potential with timing environmental and economic data. Meanwhile, the advanced BESS technology development should be updated to fully capture the potential of BESS in smoothing the intermittency of wind power.

5. Conclusions

The full potential of wind power distribution was assessed with up-to-date data (land use, landform) related the wind power exploitation and a novel method for mitigating the intermittency was used to capture the full exploitable potential of onshore wind energy. The cost of the intermittency of wind power was quantified and was included in the wind resource assessment. The novel method presented in this study provided a way of quantifying the cost of variability of wind power assessment, which can be widely applied in other regions worldwide. It also provided a new way of addressing the wind power intermittence as well.

This study found that the most profitable or suitable wind resources are located in Eastern Inner Mongolia, Hexi Corridor, and Qinghai Tibet Plateau as the wind energy density exceeds 350 W/m^2, the technical potential reaches 8000 MWh/km^2 and LCOE is less than 0.5 CNY/kWh. The vast desert and gobi in North-western China are the ideal places for wind power development. It should be also noted that BESS could be good supporting facilities for wind farms with the development of energy storage technology in the near future. Although the wind energy resource is rich in the Qinghai Tibet Plateau, the risk of exploitation is high because of the high altitude and frequent extreme weather in this region.

CRediT authorship contribution statement

Yang Gao: Methodology, Software, Data curation, Visualization, Writing - Original draft preparation. **Shaoxiu Ma:** Conceptualization, Methodology, Project administration, Writing- Reviewing and Editing. **Tao Wang:** Supervision. **Tongliang Wang & Yulai Gong:** Validation. **Fei Peng & Atsushi Tsunekawa:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank to the financial support provided by “Hundred Talent Program” of the Chinese Academy of Sciences (Y729G01002) and The National Key Research and Development Program of China (No.2017YFE0119100). Authors are grateful to the climate modelling teams (listed in Table 1) for producing and making available their model outputs.

Appendix

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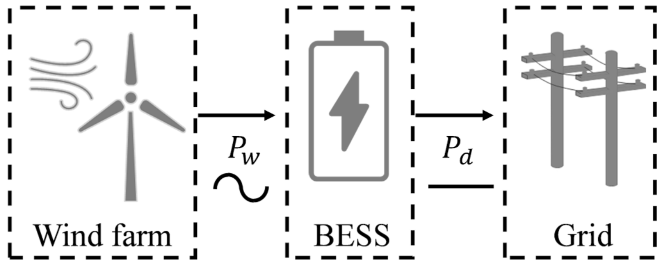

Fig. A1. Schematic diagram of wind power buffering system (BESS: battery energy storage system).

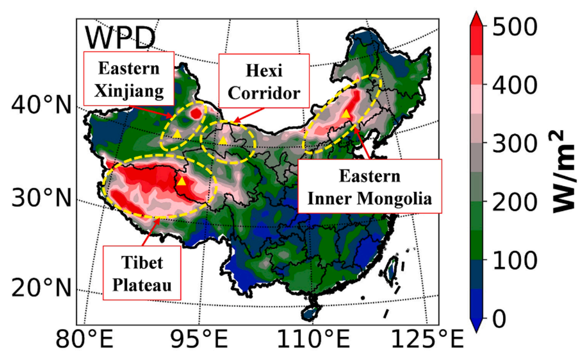

Fig. A2. Location of interesting regions (yellow circle) and sample point (yellow triangle).

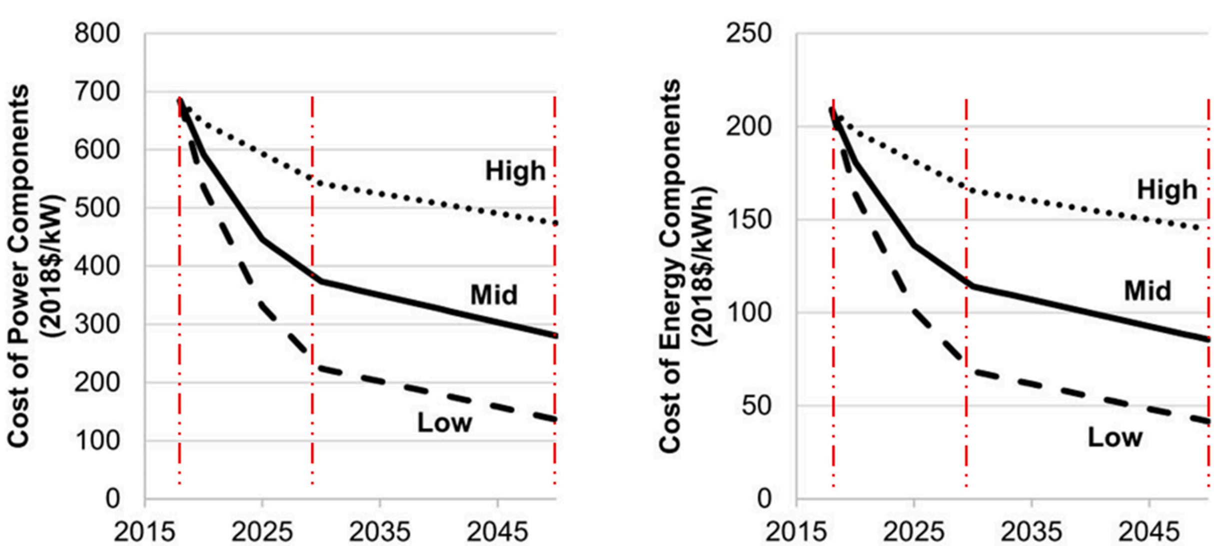

Fig. A3. Cost projections for power (left) and energy (right) components of Lithium-ion systems [58].

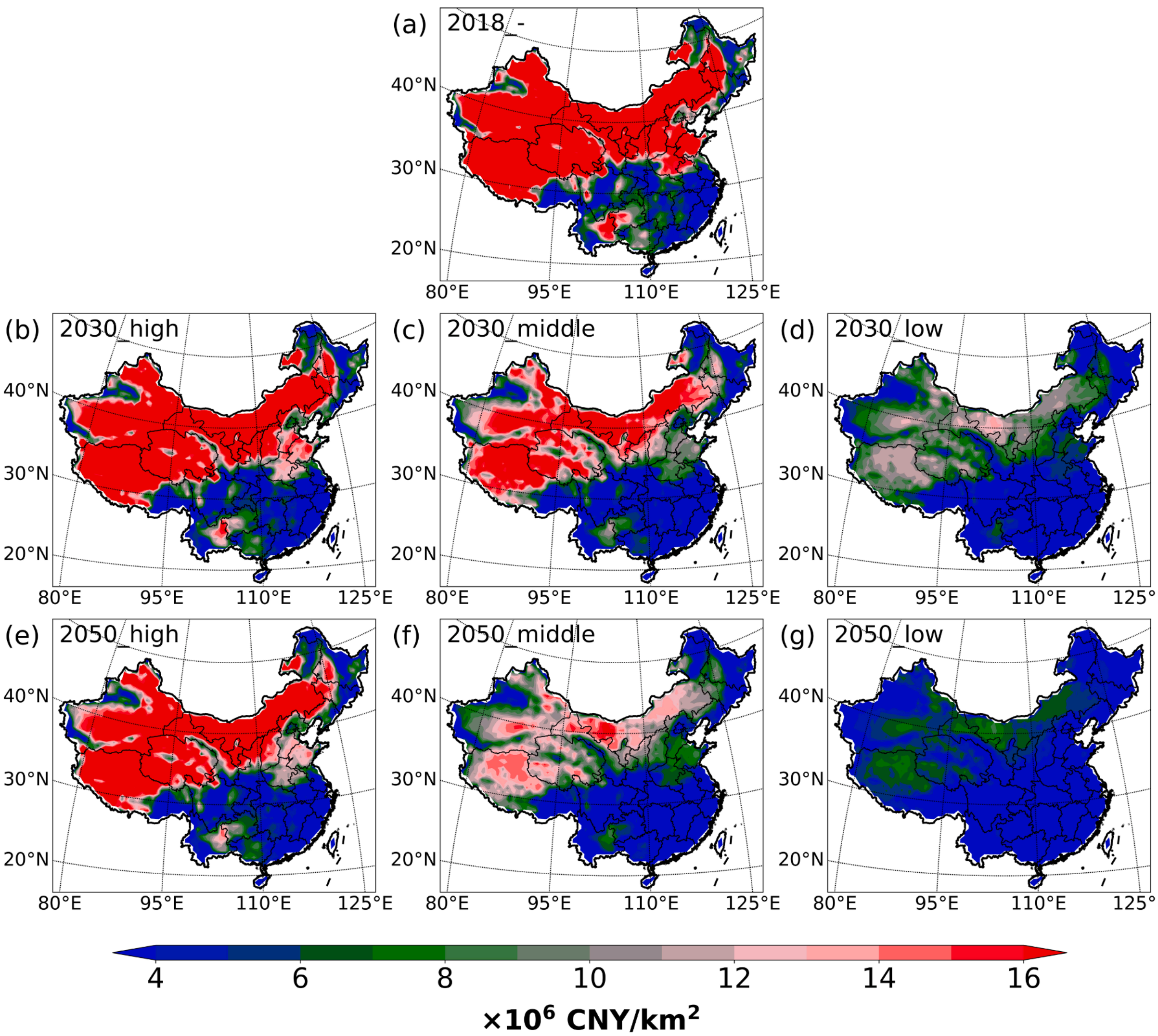

Fig. A4. The cost of battery energy storage system (BESS) calculated according Eq. (11) in 2018, 2030, 2050 (in rows) and high, middle, low price projections (in columns).

Table A1
Key parameters of the hypothetical wind turbine model used in this study.

Parameters	Value
Rated power	3 MW
Cut in wind speed	3.5 m/s
Rated wind speed	15 m/s
Cut out wind speed	25 m/s
Rotor diameter	100 m
Turbine height	80 m

Table A2
Detailed information of sample points.

Regions	Tibet Plateau	Eastern Xinjiang	Hexi Corridor	Eastern Inner Mongolia
Location (Lat, Lon)	(35°, 90°)	(40°, 88°)	(40°, 95°)	(44°, 118°)
Main land use type	Grassland	Desert / Gobi	Desert / Gobi	Grassland
Elevation (m)	4500	800	1100	1200
η_{sf}(%)	97.92	99.96	99.46	98.07
WPD (W/m^2)	550	290	340	531
EWP(MW)	0.99	0.59	0.72	0.98
$TP(\times 10^3\ MWh/km^2)$	7784	6828	8035	8259
SC(MWh)	14.12	9.14	9.95	11.93

Table A3
Price setting of the BESS under different projections in this paper derived from [58]

Time	High		Middle		Low	
	$Price_{Pb}$($/kW)	$Price_{sc}$($/kWh)	$Price_{Pb}$($/kW)	$Price_{sc}$($/kWh)	$Price_{Pb}$($/kW)	$Price_{sc}$($/kWh)
2018			626.3	209.6		
2030	540.9	165.5	373.9	113.9	223.6	68.7
2050	474.2	144.8	280.5	85.3	138.8	41.5

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